

# Next-generation large scale detectors

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## Executive Summary (~1-2 pages)

Next-generation large-scale detectors are planned to search for dark matter (DM) and  $0\nu\beta\beta$  and to study neutrinos from both artificial and natural sources. Achieving these goals generally requires (i) scaled-up target procurement and purification capabilities; (ii) large area photosensor development with low noise (e.g.  $\text{SNR} > 20$ , dark count rate  $< 40$  mcps/mm<sup>2</sup>, photodetection efficiency  $> 60\%$  for DarkSide-20k) and up to 20–80% coverage for DUNE; (iii) high voltage and electric field capabilities compatible with multi-meter drifts; and (iv) studying the effects and techniques for operating large doped noble liquid/gas detectors. The discovery capabilities of these detectors could be extended further by coupling them with a magnetic field, such to enable charge discrimination and improve momentum measurement.

Concerning target procurement, argon detectors will need new sources of underground argon (UAr) to fill large LArTPCs (e.g. a DUNE low-background module would need 7–17 kt). Reduction of  $^{39}\text{Ar}$  is expected to be  $1400\times$  relative to AAr at a cost  $\sim 3\times$  that of atmospheric argon (AAr). Xenon detectors will need  $\sim 100$  t (and potentially up to kt-scales in the future) from commercial sources, representing  $\sim 2$  years of total annual output worldwide at costs which must be coordinated with vendors. Natural Xe has sufficiently low background for future searches, and a large target can be sold back, substantially reducing its cost below the upfront acquisition cost of  $\$1\text{M/t}$ . Isotopic separation can benefit rare event searches by separating out  $^{136}\text{Xe}$  from the target (for  $\beta\beta$ -decay) and odd-neutron isotopes ( $^{129,131}\text{Xe}$ ) reduced in  $^{136}\text{Xe}$  for a DM search. However this will significantly impact the cost of the Xe.

Backgrounds generally need to be reduced to the  $\mathcal{O}(1)$  event/exposure in the  $<200$  keV<sub>nr</sub> energy range for dark matter searches and in the  $\mathcal{O}(\text{MeV})$  range for neutrino experiments. This goal requires further radiopure detector development, including the identification of radiopure pressure vessels, cryostat, and photosensor materials. Significant progress has been made in low-background SiPM development, though Xe-sensitive SiPM systems (or Xe-compatible wavelength shifters) need to be improved (especially dark rates and effective QE of large area arrays) in order for Xe detectors to transition to PMTs to SiPMs. It is also necessary to reduce radioactive impurities in the target, and enrichment is needed for Xe-based  $0\nu\beta\beta$  searches. Cryogenic distillation has come a long way in this regard, and UAr has been shown to have substantially lower  $^{39}\text{Ar}$  contamination, and  $^{42}\text{Ar}$  may be negligible. Larger sources of UAr will be

needed for applications much larger than Argo (300 t), and upgrades may be needed to Aria to achieve a high throughput for similarly large volumes. Cosmogenic activation of radioisotopes is also a challenge; new measurements may be needed to improve activation calculations.

Large-area photon- and charge-detection techniques and their associated readouts are also needed. For light detection, this includes (i) photosensor development with expanded light collection area and large-area wavelength shifters, (ii) development and production of low-background, low-noise cryogenic SiPMs ( $O(5-8) \times$  DarkSide-20k's number for a low-background DUNE module), (iii) development of power-over fiber technology and low-power, high-multiplexing cold readout electronics for photodetection empowering high timing resolution, needed to achieve  $4\pi$  light detection with high surface-coverage for 4D tracking and dual calorimetry in a LArTPC, improving the PID and energy resolution. For charge detection, the development of large-area and low-noise electron multipliers is important to detect small signals in large detectors.

Combining this lower detection threshold with a magnetic field in the range of 0.5 to 1 Tesla in the fourth DUNE module would allow for an effective measurement of momentum, charge discrimination, better energy resolution for hadron showers, improved particle identification and identification of the starting point of low energy electrons. This has the potential to add significance to the physics output of the overall observatory, for instance by improving the sensitivity to CP violation with atmospheric neutrinos by 50%. Since external conventional magnets are not suited for large volume cryogenic detectors, a robust R&D program is needed to evaluate alternatives based on superconducting magnets: these could range from warm superconductors requiring dedicated cryogenic infrastructure, such as  $MgB_2$  to be operated at 15-20 K, to hot superconductors more directly integrable in the nitrogen cooling plant or directly in the liquid argon volume, such as YBCO that can be operated at the liquid nitrogen temperature of 77 K.

LArTPC performances in the presence of a magnetic field are currently being studied in an R&D effort at Fermilab to determine minimum field requirements to achieve particle charge separation and study electron diffusion in the presence of the field.

Larger noble element TPCs require higher high voltages (HV). New HV feedthrough (FT) designs are needed for these larger areas. Successful R&D implementing a conventional HV FT was developed for the 4D-LArTPC DUNE module to obtain a homogeneous, vertical electric field of 500 V/cm over a 6.5 m drift with a  $3 \times 3 m^2$  anode plate. Examples like this can be taken as a starting point to test and develop a new technology. A FT from a co-extruded multi-layer cable made of a single plastic material with an additional semi-resistive plastic layer between the insulation and ground can robustly and compactly deliver  $>100kV$  and generate electric fields within a detector. Such a cable can be manufactured by developing a semi-resistive plastic with tunable resistivity (between  $10^7$ - $10^{13}$  Ohm cm for a thickness of 0.3 to 1 mm).

# Instrumentation requirements to achieve physics goals (list)

The following instrumentation developments are needed for next-generation large-scale detectors

- Target procurement
  - 30–80 tonnes of Xe
    - Existing industrial production is suitable
    - Commercial Xe cryogenic distillation ~50-100 tonne per year so need to work long-term with industrial partners
  - 300 tonnes UAr for Argo, potentially more for other applications
  - DUNE low-background: at least ~8 kt, up to 17 kt  
Requires identifying new source of UAr, new extraction facilities
- Large-area, low-background photodetection
  - Low-background, cryogenic Si photomultiplier development and production
    - SNR > 20, Dark count rate < 40 mcps/mm<sup>2</sup>, photodetection efficiency > 60%
    - Nuova Officina Assergi (NOA) facility developed for SiPM production at LNGS
  - For low bkgd DUNE, need ~20% coverage for 4D LArTPC or PSD background module for WIMP search ; for  $0\nu\beta\beta$  with good resolution, need closer to ~80% coverage
- Background modeling and mitigation
  - Targets:
    - DarkSide-20k target: 0.1 NR evt in ROI/(200 tonne-years) excluding neutrinos (expected within reach), (ROI [40,200] keVnr)
    - NEXT target: 0.06 ct/ton/year/ROI (arXiv:2005.06467)
    - DUNE: cryostat stainless steel 1E-11 neutrons/cm<sup>3</sup>/sec, external H<sub>2</sub>O shielding
    - LZ: [Rick]
    - Darwin: [Rick]
  - Radiopure material identification, large radiopure cryostat design and pressure vessel, radiopure PMMA
  - Reduce backgrounds internal to the target (e.g. <sup>39</sup>Ar, <sup>85</sup>Kr, <sup>136</sup>Xe)
    - In some cases, want to enrich target with <sup>136</sup>Xe, or change isotopes with odd/even A
    - For LXe TPC DM detectors, require <15 ppq <sup>85</sup>Kr to be < 10% pp neutrinos
    - Rn requirements for DUNE low-background module  
For the low background module we set a radon target level in the liquid argon of 2  $\mu$ Bq/kg. Will require inline purification, emanation suppression via handling, surface treatments, dust control, alpha tagging.

- $^{39}\text{Ar}$  reduction achieved in LAr with UAr from Urania (at least 1400× reduction), potential upgrade to Aria for 10× suppression at high-throughput (current technology can achieve this at lower throughput)
  - Cosmogenic backgrounds ( $^{137}\text{Xe}$ )
- Large volume recirculation and purification
  - Ability to stably handle LAr-Xe mixtures, other doped nobled liquids
  - Rn-removal during recirculation
- Charge collection over large drifts
  - Require high purity
- 4D tracking and dual calorimetry capability in LArTPC (4D-LArTPC)
  - Photon detection surface coverage ~O(20)%
  - Photon detection coverage at all six LArTPC's surfaces including cathode and anode planes
- Excellent timing resolution for light detection at O(1) ns with multiple activities to enable detection of signals with delayed timing signatures (kaon decay, Time of Flight ...) (4D-LArTPC)
- Doping (Xe+LAr, H or He + LXe, etc.)
- Energy resolution requirements (NEXT expects ~ 0.5% FWHM)
- Magnetic field:
  - Superconducting coil that can operate at LAr or LN temperatures and provide a field of ~1 T in the detector active volume.

## Significant instrumentation challenges (list)

- High pressure XeTPC development
  - Large scale meshes for electroluminescent region
  - Multiplexing of large number of channels
- Isotopic ( $^{39}\text{Ar}$  reduction to avoid overwhelming <MeV rates,  $^{136}\text{Xe}$  enrichment, background reduction) and chemical purification (long drift times in TPCs)
  - UAr procurement with Aria (>1400× depletion factor), purification+ $^{39}\text{Ar}$  depletion (10× at 8.1 kg/day) with Aria cryogenic distillation column,  $^{39}\text{Ar}$  assay with DArT-in-ArDM facility,  $^{42}\text{Ar}$  reduction
  - Xe cryogenic distillation, isotopic separation, Kr and Rn removal
- Batch Rn removal
  - Significant increase in circulation rate / liquid circulation / deliver in situ Rn mitigation
- Large-area photo- and charge detection
  - Photosensors w/ expanded light collection area (e.g. Arapucas, light collection modules, TPB-cladded optical fibers, etc.)
  - Large-area wavelength shifter coverage (coating large areas in TPB not always practical), e.g. PEN
  - Large-area, low-noise electron multipliers (e.g. LEMs) for charge collection in large detectors
  - In LXeTPCs

- Scaling PMTs from 7.5 cm to 12.5 cm diameter photocathodes
  - To use SiPMs, need to develop wavelength shifter compatible with LXe to increase SiPM efficiency
  - Dark rates at 160 K present significant challenge
    - Hybrid deployment with SiPM in locations where dark rate is not a penalty
  - Grid and Insulator to ensure Quiet Operation / Minimize Free Charges in Target
    - Designs to minimize light emission from biased grids
    - Minimize charge generation associated with light illumination of surfaces
- Electric fields over large areas
  - Robust **and compact** high-voltage (**>100kV**) feedthroughs needed to generate E-fields over large distances
  - **Develop a semi-resistive plastic material with a resistivity of  $10^7$ - $10^{13}$  Ohm cm for a thickness of 0.3 to 1mm which is compatible with polyethylene and can be used in coextrusion process**
  - For 4D-LArTPC DUNE module, requirements have been demonstrated for 6.5 m at 500 V/cm
- Power transmission
  - Power-over-fiber technology for light detectors as well as readout electronics, so that light detectors can be implemented on the cathode and possibly field cages (4D-LArTPC)
- Development of low-power and high-multiplexing cold electronics to enable high optical photon surface detection coverage (4D-LArTPC, LXeTPCs, HPGXeTPCs for energy and topology too)
  - Overlap with ASIC development
- Realization of magnetic fields in the range of 0.5 to 1 Tesla for large mass LAr-TPC detectors such as one of the DUNE modules
  - Warm superconducting coils (such as  $\text{MgB}_2$  @ 15-20 K), require dedicated and large cryogenic system external to the detector volume.
  - Hot superconducting coils (such as YBCO @ 77 K) offer several advantages both in terms of the simplification of the cryogenic plant and for the potential development of industrial applications, but are very expensive.
  - Integrating the LAr TPC technology with a large volume magnet is a significant challenge, mostly from the engineering point of view: arrangement of the coils, handling of the return field, compatibility of materials and equipment both for cryogenics, purification systems, cryostat and detector components.

## Relevant physics areas

- Dark matter detection (high mass, low mass, dark photons, ...)
- Search for nucleon decay
- Precision Measurements of neutrino oscillations:

- Search for CP violation, neutrino mass ordering, octant determination, unitarity tests of PMNS matrix ...
- $0\nu\beta\beta$  and sterile neutrino searches
- Non-standard neutrino interactions
- Atmospheric, solar, and supernova neutrino measurements

## Relevant cross-connections

- NF1 neutrino oscillation,
- NF-10 neutrino detectors
- E. Angelico, A. Elagin, H. J. Frisch, and M. Wetstein, "Measuring the Neutrino Event Time in Liquid Argon by a Post-Reconstruction One-parameter Fit"

## Further reading

- CDR for Vertical-Drift Single Phase DUNE far detector (4D-LArTPC)
  - [https://edms.cern.ch/file/2619631/1/Vertical\\_Single\\_Phase\\_FD\\_Technology\\_CD\\_R.pdf](https://edms.cern.ch/file/2619631/1/Vertical_Single_Phase_FD_Technology_CD_R.pdf)
- LOIs:
  - "[The exploitation of Xe large scale detector technology for a range of future rare event physics searches](#)"
  - "[High-pressure xenon gas time-projection chambers for neutrinoless double-beta decay searches](#)"
  - "[Instrumentation and R&D for the Global Argon Dark Matter collaboration](#)"
  - "[DUNE near detector](#)"
  - "[Low background kTon-scale liquid Argon time projection chambers](#)"
  - "[High voltage cable feed-through](#)"
  - "[Development of LArTPC with  \$4\pi\$  light detection to enable 4D tracking and dual calorimetry capabilities \(4D-LArTPC\)](#)"
  - "[Magnetizing the Liquid Argon TPC](#)"
  - "[Solution-mined salt caverns as sites for underground physics experiments](#)"